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Cooling process on a run-out table by the simulation method

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ABSTRACT

This study aims to determine the effective cooling parameters for the run-out table (ROT) of strip steel in a hot rolling process. Two-dimensional transient heat conduction is developed, including the external force convection and heat source due to translational motion. The strip velocity, cooling water temperature and external fluid velocity are chosen to study the influent parameters during the cooling process. To determine 2-dimensional transient heat conduction in the cooling process of strip steel, numerical methods are applied to solve for the temperature of the strip steel with appropriate boundary conditions. The backward difference formula (BDF) applies to the discretization of a partial differentiation equation (PDE). The parallel sparse direct linear solver (PARDISO) is applied to the computation in the form of a linear algebraic equation built with the Comsol multiphysics software for the heat transfer module. The simulation studies are divided into 12 case studies with three variations subjected to cooling conditions at the ROT. From the results of the simulation study, appropriate parameters to determine the temperature required for strip steel are achieved.

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1. Introduction

Recently developed advanced material processing technology is suitable for achieving low production costs, high productivity, and better quality products. The manufacturing process for steel production is time consuming. Slap products are passed through several machines, such as a roughing mill and a finishing rolling mill, to gain the desired size of the product. After the finishing rolling stand stage, the steel strip type is defined. Mechanical and physical properties of the steel strip are controlled to achieve the desired product quality. Temperature is one of the main parameters that are used to control the product properties. After the finishing stand process, the next process for the strip steel is to arrive at the run-out table (ROT), as depicted in Fig. 1. The run-out table (ROT) cools the temperature from approximately 800–950 °C at the entrance to 450–600 °C at the exit from the ROT. If the temperature is cooled linearly, as described, then the phase transformation of the metallurgical structure of the strip steel will change from the austenite to the ferrite range of grain sizes. The water wall cools the strip temperature with a nozzle jet at both the bottom and the top of the strip surface. To conserve water in the cooling process at the ROT, optimal control of the cooling parameters during cooling is required, and this study was performed to determine the necessary cooling parameters and the method by which to control them. In this study, three variables, such as strip velocity, external fluid velocity, and cooling water temperature, are used to produce the cooling conditions at the ROT and to study the effective cooling variables. The problem of determining the optimal cooling variables for cooling during the ROT process is derived for an operational method in a practical manner.

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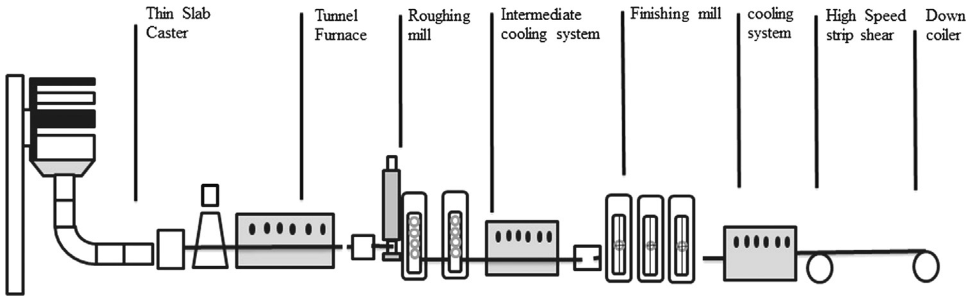

Fig. 1. Layout of the hot rolling process in strip steel production.

Many researchers have attempted to analyze the cooling system at the run-out table (ROT). Mukhopadhyay and Sikdar [1] implemented an online run-out table model in a hot steel mill. Coiling temperature is the main parameter for performing online cooling at the run-out table by using the inversion temperature control technique. This study developed only a 1D conduction transient heat transfer and did not consider strip velocity. Sun et al. [2] predicted the thermal and metallurgical behavior by using a finite element model at the run-out table. Finite element coupled analysis of the thermal and metallurgical behavior of the strip occurred at the run-out table for the hot strip rolling process. Additional predictions of the temperature and phase transformation at the run-out table were also described by [3,4].

Serajzadeh [5] also modeled the temperature history and phase transformations during the cooling of steel by using the finite element model. The simulation for the prediction of temperature and phase transformations was compared to the experimental methods to validate the proposed prediction model. The model of the deformation, temperature and phase transformation behavior of strip steel on the run-out table was presented in the numerical model to simulate the behavior that was followed. The thermal model was formulated by using finite elements and the heat transfer coefficient of the strip from actual mill data. The additional model included the deformation behavior in the model proposed by Han et al. [6] Edalatpour et al. [7] presented the prediction accuracy of the strip temperature due to the effect of phase transformation latent heat in laminar cooling. The model used to calculate the strip temperature and volume fraction of the steel phase during cooling at the run-out table encountered different situations depending on whether phase transformation latent heat was considered or the phase transform latent heat was disregarded. In addition to the essential study on the prediction of the temperature and phase transformation, Wang et al. [8] extended their studies to describe the calculation of the thermal stress affecting the strip flatness change during the run-out table cooling of the hot strip steel. The finite element was used to analyze the thermal stress during cooling. The commercial finite element software ABAQUS was used to analyze and calculate thermal behavior. Previous studies [9,10] also studied the cooling system. The experiment in the present study has been designed to study the effect of cooling parameters at the run-out table. Most of the previous investigations have studied the thermal and metallurgical behavior of the strip during cooling at the run-out table. The prediction of the temperature and phase transformation is crucial in the literature studies to achieve the desired quality in the strip product. In the present study, we aim to determine the effect of the cooling parameters on strip steel at the ROT of a hot rolling process.

2. Mathematical Model

2.1. Conduction heat transfer model

The mathematical model of heat conduction in the strip at the run-out table can be formulated by rectangular coordinates to describe the thermal behavior. The physical state of the system is modeled in a two-dimensional heat transfer equation for the moving strip. The transient analysis of heat transfer for the moving strip can be described by Eq. (1), as explained by Serajzadeh [4].

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c u_i\frac{\partial T}{\partial x}+\rho c\frac{\partial T}{\partial t} \tag{1}$$

where ρ is the density, c is the temperature-dependent specific heat, k is the temperature-dependent thermal conductivity of the material, u_i is the strip velocity, and T and t are temperature and time, respectively. The parameter $\dot{q}$ is the heat generation term representing the internal heat source released due to phase transformation.

2.2. Boundary and initial conditions

The differential equation needs to be solved by numerical methods. Heat conduction occurs on the slap surface. Convection heat transfer is applied to the force convection and natural convection using water and air, respectively. At the run-out table, the conduction of heat transfer on the strip surface can be set to the boundary conditions by Eq. (2).

$$-k\frac{\partial T}{\partial z}=h_w(T-T_w) \tag{2}$$

where z is the normal direction of the surface of the strip and h_w is the coefficient of convection heat transfer by water on the strip surface. T_w is the temperature of water, and T is the strip temperature.

Boundary conditions at the inlet region are shown in Eq. 3.

$$T(0,z)=T(z) \tag{3}$$

Boundary condition at the outlet region are shown in Eq. 4.

$$\left.\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right|_{\mathrm{x=L}}=0 \tag{4}$$

The initial conditions are set by Eq. (5)

$$T(x,z,t=0)=T_{0,0} \tag{5}$$

where $T(z)$ is the temperature distribution along the thickness after the work at the rolling stand is finished. L is the length of the run-out table.

3. Numerical Solution

3.1. Discretization methods

The backward difference formula (BDF) is applied to estimate the first and second order derivative equations. Discretization can, therefore, be evaluated for the continuous time of the derivation. The time-dependent problem is solved by using an implicit time stepping scheme. The step time (Δt) must be small, with a uniform grid, in spatial rectangular domain, and it can be calculated for uniform conductivity by Eq. (6) for an equal space grid. Spatially coordinate by the (x,z) is referred to [11,12].

$$\Delta t<\frac{\rho c(\Delta x)^2}{2k} \tag{6}$$

The final discretization that is approximated by using the implicit time stepping method can be expressed in Eq. (7) by neglecting the source term, $\dot{q}$.

$$\frac{T_{i,j}-2T_{i-1,j}+T_{i-2,j}}{\Delta x^2}+\frac{T_{i,j}-2T_{i,j-1}+T_{i,j-2}}{\Delta z^2}=\frac{\rho c}{k}u\frac{T_{i,j}-T_{i-1,j}}{\Delta x}+\frac{\rho c}{k}\frac{T_{i,j}-T_{i-1,j}}{\Delta t} \tag{7}$$

The updated time derivative of the model can be calculated to the specifications of the time stepping interval. Based on an implicit time stepping method, the iterative solution can be formulated by using the finite difference method. Because u_i is the strip velocity with a unidirectional translational motion, the PDE for heat transfer referred to in Eq. (1) can be solved by the implicit finite difference equation, using the upwind scheme. It follows to discretization in Eq. (8).

The forward time derivative for $(\partial T/\partial t)$ is used, and the backward derivative for$(\partial T/\partial x)$, $(\partial^2 T/\partial x^2)$ and $(\partial^2 T/\partial z^2)$ is used. This results in the upwind scheme are shown in Eqs. 8 and 9.

$$\frac{\rho c}{k}\frac{T_{i,j}^{n+1}-T_{i,j}^{n}}{\tau}=\frac{T_{i,j}^{n}-2T_{i-1,j}^{n}+T_{i-2,j}^{n}}{\Delta x^2}+\frac{T_{i,j}^{n}-2T_{i,j-1}^{n}+T_{i,j-2}^{n}}{\Delta z^2}-\frac{\rho c u_i}{k}\frac{T_{i,j}^{n}-T_{i-1,j}^{n}}{\Delta x} \tag{8}$$

and

$$T_{i,j}^{n+1}-T_{i,j}^{n}=\frac{k\tau}{\rho c\Delta x^2}\left(T_{i,j}^{n}-2T_{i-1,j}^{n}+T_{i-2,j}^{n}\right)+\frac{k\tau}{\rho c\Delta z^2}\left(T_{i,j}^{n}-2T_{i,j-1}^{n}+T_{i,j-2}^{n}\right)-\frac{k\tau}{\rho c}\frac{\rho c u_i}{k\Delta x}\left(T_{i,j}^{n}-T_{i-1,j}^{n}\right) \tag{9}$$

The formulation of each numerical method is shown below. The parameters Δx and Δz represent the space between two space grid points or the space step size, and τ is used to represent Δt, the time step. The above Eq. (8) is modified by evaluating the space backward derivative at time step $n+1$ instead of at time step n, resulting in Eq. (10).

$$T_{i,j}^{n+1}-\frac{k\tau}{\rho c\Delta x^2}\left(T_{i,j}^{n}-2T_{i-1,j}^{n}+T_{i-2,j}^{n}\right)-\frac{k\tau}{\rho c\Delta z^2}\left(T_{i,j}^{n}-2T_{i,j-1}^{n}+T_{i,j-2}^{n}\right)+\frac{k\tau}{\rho c}\frac{\rho c u_i}{k\Delta x}\left(T_{i,j}^{n}-T_{i-1}^{n}\right)=T_{i,j}^{n} \tag{10}$$

By rearranging the discretization equation, we obtain the final result in Eq. (11).

$$T_{i,j}^{n}=T_{i,j}^{n+1}-\frac{\tau k}{\rho c\Delta x^2}T_{i,j}^{n+1}-\frac{\tau k}{\rho c\Delta z^2}T_{i,j}^{n+1}+\frac{\tau u_i}{\Delta x}T_{i,j}^{n+1}+\frac{\tau k}{\rho c\Delta x^2}2T_{i-1,j}^{n+1}-\frac{\tau u_i}{\Delta x}T_{i-1,j}^{n+1}+\frac{\tau k}{\rho c\Delta z^2}2T_{i,j-1}^{n+1}-\frac{\tau k}{\rho c\Delta x^2}T_{i-2,j}^{n+1}-\frac{\tau k}{\rho c\Delta z^2}T_{i,j-2}^{n+1} \tag{11}$$

Rearranged into a new form, Eq. (11) can be represented by Eq. (12).

$$a_pT_{i,j}^{n+1}+a_{w-1}T_{i-1,j}^{n+1}+a_{w-2}T_{i-2,j}^{n+1}+a_{s-1}T_{i,j-1}^{n+1}+a_{s-2}T_{i,j-2}^{n+1}=T_{i,j}^{n} \tag{12}$$

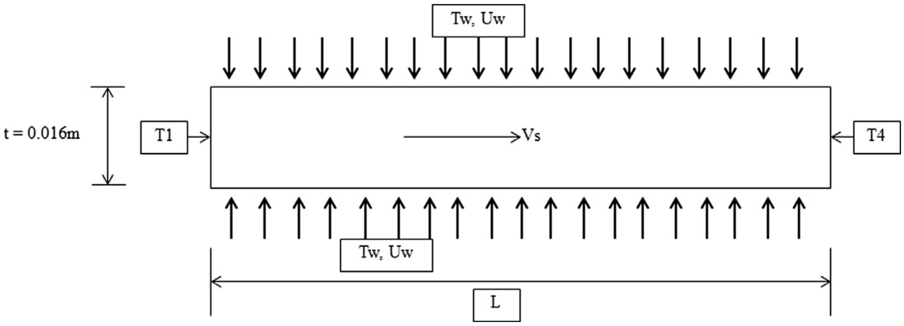

Fig. 2. Boundary and condition setting.

Where

$$a_p = 1 - \frac{\tau\alpha}{\Delta x^2} - \frac{\tau\alpha}{\Delta z^2} + \frac{\tau u_i}{\Delta x}$$

$$a_{w-1} = \frac{2\tau\alpha}{\Delta x^2} - \frac{u_j \tau}{\Delta x}$$

$$a_{w-2} = -\frac{\tau\alpha}{\Delta x^2}$$

$$a_{s-1} = \frac{2\tau\alpha}{\Delta z^2}$$

$$a_{s-2} = -\frac{\tau\alpha}{\Delta z^2}$$

where $\alpha = (k/\rho c)$ is the constant of the material; this will be stable if $(\tau u_i/\Delta x) \le 1$ and $(\tau\alpha/\Delta x^2) \le 1$ and $(\tau\alpha/\Delta z^2) \le 1$.

4. Simulation Model

In the simulation, we set boundaries and conditions for the 2D heat transfer model, as illustrated in Fig. 2. The details are listed below.

- 2D heat conduction transfer in a transient analysis
- Strip dimension of $0.016 \times 47\ m$
- Steel type AISI 4340
- Convective cooling with water at a total plate length of 47 m, with an average heat transfer coefficient (h_w) by external force convection
- Initial value for strip temperature of 1148 K
- T1 = 1148 K
- T4 = 793 K
- No heat source, Q
- No heat flux generation at all boundaries
- Strip velocity: (V_s) (m/s)
- External fluid velocity: (U_w) (m/s)
- Temperature of cooling water: (T_f) $(°K)$

This study utilizes the Comsol Multiphysics software made by I-MATH PTE LTD 10 Ubi Crescent Ubi Techpark #06-37 Singapore to build and solve the model with the numerical methods in [13,14]. The model that is developed is established in the configuration as shown in Fig. 2. In this study, parameters that are changed, the variables for simulation, are constrained by three variables, such as strip velocity (V_s), external fluid velocity (U_w) and cooling water temperature (T_f). These effect the control strip temperature at the entrance and exit of the ROT and are shown in Table 1 for a case study simulation. The mesh consistency of the simulation is shown in Fig. 3.

At the run-out table for the cooling process of strip steel, we specify the strip temperature at the entrance of the ROT and at the exit of the ROT, as indicated in Table 2. To maintain the desired product quality and specificity, the cooling process requires the control of the strip temperature after the exit of the ROT, as shown in Table 2. The aim of the simulation study is to verify the minimum strip temperature error compared to the reference strip temperature at the exit of the ROT, as shown in Table 2. Percent true relative error is useful, as computed by Eq. (13).

$$\varepsilon_t = \frac{True\ error}{True\ value} \times 100 \tag{13}$$

Table 1
Case study simulation by varying three variables.

Case study	Strip Velocity (V_s) (m/s)	Fluid Velocity (U_w) (m/s)	Cooling water temperature (T_f) (K)
1	$V_s=10$	$U_w=20$	$T_f=288$
2	$V_s=10$	$U_w=20$	$T_f=293$
3	$V_s=10$	$U_w=30$	$T_f=288$
4	$V_s=10$	$U_w=30$	$T_f=293$
5	$V_s=7$	$U_w=20$	$T_f=288$
6	$V_s=7$	$U_w=20$	$T_f=293$
7	$V_s=7$	$U_w=30$	$T_f=288$
8	$V_s=7$	$U_w=30$	$T_f=293$
9	$V_s=0$	$U_w=20$	$T_f=288$
10	$V_s=0$	$U_w=20$	$T_f=293$
11	$V_s=0$	$U_w=30$	$T_f=288$
12	$V_s=0$	$U_w=30$	$T_f=293$

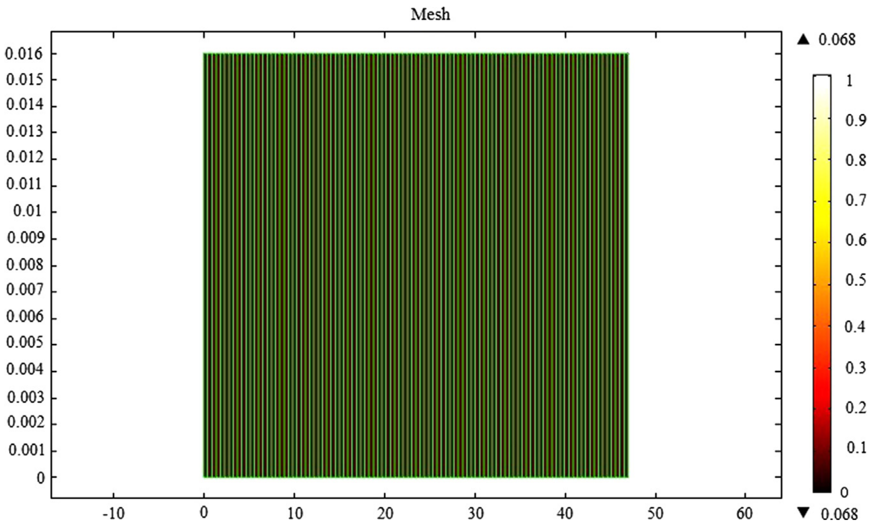

Fig. 3. Mesh consistency.

Table 2
Output of the surface temperature at the ROT

Case study no.	Entrance ROT temperature (K)	Reference at exit ROT temperature (K)	Actual surface temperature (K)	True error	Percent relative error (ε_t)
1	1148	793	754.31	38.69	0.05
2	1148	793	720.7	72.3	0.09
3	1148	793	458.85	334.15	0.42
4	1148	793	455.25	337.75	0.42
5	1148	793	679.96	113.04	0.14
6	1148	793	455.25	337.75	0.42
7	1148	793	679.96	113.04	0.14
8	1148	793	503.6	289.4	0.36
9	1148	793	441.85	351.15	0.44
10	1148	793	440.4	352.6	0.44
11	1148	793	375.32	417.68	0.51
12	1148	793	378.7	414.3	0.52

From the simulation results, we found that the minimum percent relative error of the surface temperature for the cooling process at the ROT is indicated by case study number 1 and 2. The largest percent true relative error is shown in case study number 11 and 12. The output of the strip temperature from the simulation program for case study number 1, by using Comsol Multiphysics software, is illustrated in Fig. 4.

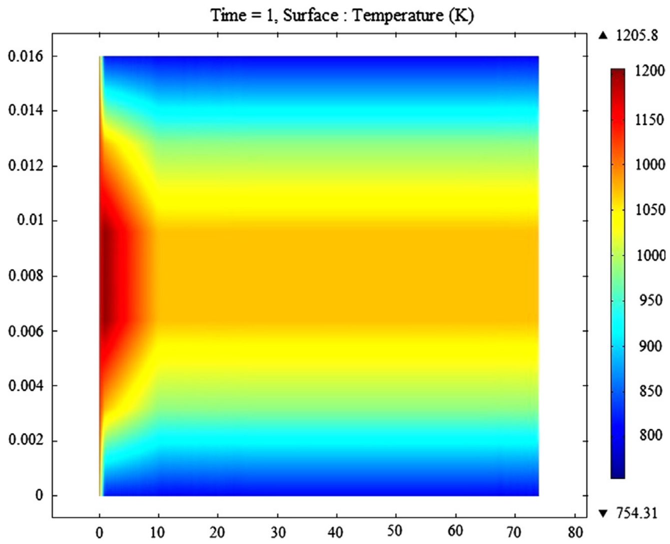

Fig. 4. Temperature layer of strip steel.

5. Conclusions

This study aims to study the effective cooling parameters at the ROT for strip steel in a hot rolling process. The desired quality of product must be controlled for throughout all of the production processes. In the cooling process, the efficiency of the ROT operating process parameters is needed for the resulting steel quality. To determine the appropriate operating parameters for the ROT cooling process, we develop the 2-dimensional transient heat transfer of strip steel by using a mathematical model. Boundary and initial conditions are bounded variables with practical constraint conditions. A numerical solution is applied to solve the mathematical model that is constructed with the Comsol multiphysics software for a heat transfer module. The simulation study is composed of 12 case studies. There are three variable parameters that are useful for each simulation in case studies, such as strip velocity, external fluid velocity and temperature of cooling water. From the simulation study, minimum errors are shown for case study number 1 and number 2. The simulation study for the ROT cooling process is achieved for establishing practical process parameters for strip steel production in material processing plants.

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